Crowding in public transport systems: effects on users, operation and implications for the estimation of demand

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Abstract

The effects of high passenger density at bus stops, at rail stations, inside buses and trains are diverse. . This paper examines the multiple dimensions of passenger crowding related to public transport demand, supply and operations, including effects on operating speed, waiting time, travel time reliability, passengers' wellbeing, valuation of waiting and in-vehicle time savings, route and bus choice, and optimal levels of frequency, vehicle size and fare. Secondly, crowding externalities are estimated for rail and bus services in Sydney, in order to show the impact of crowding on the estimated value of in-vehicle time savings and demand prediction. Using Multinomial Logit (MNL) and Error Components models, we show that alternative assumptions concerning the threshold load factor that triggers a crowding externality effect do have an influence on the value of travel time (VTTS) for low occupancy levels (all passengers sitting); however, for high occupancy levels, alternative crowding models estimate similar VTTS. Importantly, if demand for a public transport service is estimated without explicit consideration of crowding as a source of disutility for passengers, demand will be overestimated if the service is designed to have a number of standees beyond a threshold, as analytically shown using a MNL choice model.

1. Introduction

The empirical assessment of modal choice in transport has traditionally relied on time and cost as the main attributes influencing people's travel decisions. Nevertheless, with the improvement of both our understanding of the modal choice problem and analytical tools (e.g., discrete choice models), we have accumulated unambiguous evidence that shows how users take into account several qualitative aspects that enhance or harm the experience of travelling. In the case of public transport, this includes the number of passengers that have to share a bus or train, the quality of seats and the smoothness of the ride, among many others. The relevance of these qualitative aspects for public transport policy is expected to increase over time in both developing and developed economies, because as the income of a population increases, public transport users are likely to attach more value to quality and comfort features, relative to reductions in travel time only. This paper analyses the effects of having a significant number of people sharing a limited space while using a public transport service on both demand and supply, which is usually referred to as passenger crowding in the economic and engineering literature of public transport[1].

Together with travel time, cost, trip time reliability and service frequency, crowding is now seen as having a significant influence on modal choice through the value attached to reducing crowding in all its definitional variants. As people react in several ways when a dense human containment is faced, the reasons behind passengers' dislike for crowding on public transport services seem to go far beyond the simple physical discomfort that is caused by having to stand or to share a limited space with several passengers. A myriad set of sensorial, psychological and social issues have been suggested as related to high levels of passengers' density, including perceptions of risk to personal safety and security (Cox et al., 2006; Katz and Rahman, 2010), increased anxiety (Cheng, 2010), stress and feeling of exhaustion (Lundberg, 1976; Mohd Mahudin et al., 2011; 2012), a feeling of invasion of privacy (Wardman and Whelan, 2011), possible ill-health (Cox et al., 2006; Mohd Mahudin et al., 2011), propensity to arrive late at work (Mohd Mahudin et al., 2011) and a possible loss in productivity for passengers that work while sitting on a train (Fickling et al., 2008; Gripsrud and Hjorthol, 2012).

Crowding is related to a high density of passengers on vehicles, accessways and stations. A technical advantage of this phenomenon is that density can be quantitatively assessed, although there is no a single measure. The most common metric used in quantitative assessment is the occupancy rate or load factor, which is defined as the ratio between the actual number of passengers inside vehicles and the number of seats (Whelan and Crockett, 2009). Other authors use the nominal capacity of a vehicle (including both seating and standing) to measure the load factor (Oldfield and Bly, 1988; Jara-Díaz and Gschwender, 2003); using this definition we could suggest that, for example, if the load factor is over 80 percent, a vehicle can be regarded as crowded. However, none of the load factor definitions help to provide a clear indication of the degree of crowding suffered by passengers standing, which is more accurately captured by computing the density of standees per square metre (Wardman and Whelan, 2011). For example, a load factor of 150 percent, relative to the seating capacity, indicates that one out of three passengers is standing, but it does not say

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[1] Although authors like Cox et al. (2006) and Mohd Mahudin et al. (2011,2012) suggest that the concepts of "(high) density" and "crowding" should not be treated as synonyms as the latter (crowding) is a subjective interpretation of the physical phenomenon represented by the former (density).

anything about the density conditions of those standing. On the other hand, a standing density of four or five passengers per square metre is a very likely indicator of crowding discomfort, regardless of the size or capacity of a bus or train.

The crowding phenomenon is included in demand models by specifying utility functions that are sensitive to crowding in any of its physical constructs (Douglas and Karpouzis, 2005; Kim *et al.*, 2009; Whelan and Crockett, 2009; Hensher *et al.*, 2011; Fröhlich *et al.*, 2012), thereby modellers have shown that the value of both waiting and in-vehicle travel time savings may increase as a function of the number of people in stations, vehicles and carriages, producing a crowding externality or crowding cost. If users dislike crowding, the inclusion or omission of the crowding cost influences the optimal values of service frequency, vehicle size and fare level, among other supply side variables (Kraus, 1991; Jara-Díaz and Gschwender, 2003; Tirachini *et al.*, 2010a, 2010b). The existing literature provides clear indications that crowding matters to users; however, none of these studies has analysed what is the influence of ignoring the existence of crowding disutility on the valuation of travel time savings, and ultimately on demand prediction.

The aim of this paper is twofold. First, we present a comprehensive review of the multiple dimensions of crowding effects and high passenger density on public transport demand, supply and operations, including the impact on travel time, waiting time, service reliability, value of travel time savings, passengers´ wellbeing and optimal supply and pricing (Section 2). Second, we analyse the implications of ignoring the existence of crowding disutility on the valuation of travel time savings and on demand prediction (Sections 3 and 4), by estimating Multinomial logit (MNL) and Error Components (EC) models using data from Sydney, Australia. The comparison of estimated values of in-vehicle time savings and demand with and without accounting for the crowding phenomenon reveals the problems of omitting people's perception of crowding when estimating demand for public transport. Finally, the main conclusions of the paper are summarised in Section 5.

2.   Effects of Passenger Density and Crowding

2.1   Effect on in-vehicle time

When buses and trains circulate with a low number of passengers, everyone is able to find a seat, transfer of passengers at stations is smooth, and passenger-related disruptions that impose unexpected delays are rare. As the number of passengers increase, a threshold is reached at which not everyone is able to find a seat and some users need to stand inside vehicles. In turn, this may make more difficult the movement of other passengers that need to board to or alight from a vehicle; therefore, riding time increases due to friction or crowding effects among passengers.

The crowding effect on increasing boarding and alighting times has been captured by a number of authors who have estimated dwell time functions for trains and buses under uncrowded and crowded operation. Lin and Wilson (1992) estimate dwell time models for light rail trains in the Massachusetts Bay and find a statistically significant friction effect between passengers alighting and those standing at stations to board, and between passengers boarding and those that are standing inside trains. The authors estimate linear and non-linear dwell time models on crowding, with the latter providing a slight better fit to

the observed data than the former. A later analysis over the same light rail system by Puong (2000) showed that the interaction between boarding passengers and through standees is well explained by a cubic term on the number of passengers standing around a door; the average boarding time is 2.3 seconds per passenger (s/pax) in uncrowded conditions but raises to 2.9 and 4.4 s/pax with 10 and 15 through standees per door, respectively.

In the case of buses, models that show how crowding levels increase boarding and alighting times have been empirically estimated using data from several cities around the world, including Santiago de Chile (Gibson et al., 1997), Chicago (Milkovits, 2008), Dhaka (Katz and Garrow, 2012), Vancouver (Fletcher and El-Geneidy, 2013) and Sydney (Tirachini, 2013). Milkovits (2008) finds that dwell time increases with the square of the number of standees inside a bus, multiplied by the total number of passengers boarding and alighting at a bus stop. Like in the previously described rail models, this quadratic term captures the increased friction amongst passengers when the number of standees is high. Along these lines, Fletcher and El-Geneidy (2013) find that the crowding effect increases dwell times once 60% of the occupancy of vehicles is reached.

Two studies point to the fact that crowding inside buses might be more problematic for alighting than for boarding. Fernández (2011) performed laboratory experiments with a full-size bus model in London, to find that average boarding times increase linearly and average alighting times increase exponentially as a function of density of passengers inside the vehicle (from 1 to 6 passengers per square metre, pax/m^2). In particular, average boarding and alighting times are lower than 1.9 s/pax for densities lower than 4 pax/m^2, however with a density of 6 pax/m^2 average boarding time is 2 s/pax but average alighting time escalates to 5.9 s/pax, explained by the difficulties of alighting passengers walking among too many standees. On the other hand, the study of Tirachini (2013) uses empirical data from buses in Sydney and estimates thataverage boarding and alighting times increase 0.34 and 0.56 seconds per passenger, respectively when there are passengers standing in the bus aisle relative to uncrowded conditions. On the engineering side, Katz and Garrow (2012) find that bus design factors (e.g., front seating area, placement of doors, fare collection system) influence the amount of people that stand near doors, which has a larger impact on increasing dwell times than the number of passengers standing in aisles. For example, on buses with two doors with one door at the front, having the second door at the middle of the bus significantly increases the crowding effects due to standees than having the second door at the back of the bus.

The limited capacity of bus stops and train stations may also represent a problem if a large volume of passengers need to be handled at the same time, particularly in those stations in which many bus services stop. In such cases, some passengers may take longer to reach a door to board a vehicle if several other people are standing in his/her way, or obstructing his/her line of sight to sign and approach an incoming bus (TRB, 2003; Jaiswal et al., 2007; 2010). Passengers inside buses may also face difficulties leaving a vehicle if the station is crowded. These station-related crowding issues have also been analysed in the literature; for example Lin and Wilson (1992) estimate the marginal friction effect between passengers alighting and those standing at stations to board, while Gibson et al. (1997) in Santiago de Chile and Jaiswal et al. (2010) in Brisbane find that the boarding time per passenger also depends on how congested is the platform at bus stations.

2.2   Effect on waiting time

When the number of passengers is low relative to the capacity of a public transport route, users are able to board the first vehicle that arrives at their bus stop or train station. Nonetheless, when the occupancy rate is high, having a limited capacity becomes an issue, as the chance of buses or trains circulating full in some sections increases, which consequently implies that passengers waiting to board are left behind, increasing waiting time and the discomfort of travel. A formal treatment of this phenomenon was presented by Oldfield and Bly (1988) in their analysis of optimal bus size. The authors proposed that average waiting time is related not only to the headway (the inverse of bus frequency), but also to the occupancy rate or crowding level in an additive or multiplicative way.

The effect of high demand on increasing waiting times for passengers has received considerable attention in the literature on passengers' assignment to public transport networks. Spiess and Florian (1989) considered that the travel cost per link is a function of the passenger flow, to internalise the fact that waiting time and in-vehicle comfort may be a function of how many passengers use the service. On the other hand, Cominetti and Correa (2001) and Cepeda *et al.* (2006) model waiting time as inversely proportional to the *effective frequency*, which is a function of the actual frequency that decreases with the occupancy rate of buses upstream of a bus stop. The assignment model of Kurauchi *et al.* (2003) introduces that passengers may be risk-averse in their behaviour regarding what line or service to use, and therefore, be more prone to choose routes in which occupancy levels are lower, as a way to reduce the chance of failing to board a bus (for the effect of sitting and standing probabilities on route choice, see Section 2.6). In real-world applications, the increase in waiting time due to capacity constraints has been considered in the estimation of public transport load and demand in large scale scenarios including London (Department of Transport, 1989; Maier, 2011), Winnipeg, Stockholm and Santiago de Chile (Florian *et al.*, 2005), Los Angeles and Sydney (Davidson *et al.*, 2011) and San Francisco (Zorn *et al.*, 2012).

A second effect of high occupancy levels on waiting times is the possibility of triggering bus bunching (Abkowitz and Tozzi, 1987). When a bus is full and does not stop to pick up passengers at a bus stop (or if it stops but it is unable to load all passengers waiting), a larger number of passengers than is expected are left to wait for the next bus, which will need to stop for a longer period of time to board the increased number of passengers, presuming it too has capacity to accept the additional passenger load. As such, this second bus will likely be delayed and run late, decreasing its headway relative to the next bus behind, and increasing its headway with respect to the next bus ahead, a phenomenon that is amplified as buses advance along the route if control measures like bus holding are not applied (Sun and Hickman, 2008; Daganzo, 2009; Delgado *et al.*, 2009; Sáez *et al.*, 2012). In short, bus bunching leads to variability in headways, which increases average waiting time (Welding, 1957).

2.3   Effect on travel time reliability

We have discussed that when the occupancy of buses or trains approaches capacity, there might be an increase in both waiting and in-vehicle times. The inherent randomness of public transport demand, however, makes those delays difficult to predict. In other words, when occupancy rates are always low, users know that they will board the first bus that approaches their stops; nevertheless when the occupancy rate is high on average,

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passengers do not know for sure if the next bus will have spare capacity or will be full, implying having to wait for at least another bus, i.e., there might be an increase in waiting time. This is a source of unpredictability of travel times, which adds to the generalised cost of travel beyond an increase in average waiting time, because a higher variability in travel times is negatively valued by travellers as shown by the growing body of research on the valuation of travel time variability and reliability (e.g., Senna, 1994; Bates *et al.*, 2001; Bhat and Sardesai, 2006; Li *et al.*, 2010; Börjesson *et al.*, 2012).

A second issue worth of note is the likely relationship between high occupancy levels and the occurrence of incidents at bus stops or train stations, which is a source of unexpected delays that affect the service performance and reliability (beyond the phenomenon of bus bunching mentioned in Section 2.2). A common example of this situation is the case of passengers blocking the closing of doors in trains in order to enter a crowded carriage, thereby introducing an extra delay in the process of closing doors (that might include several seconds for safety reasons).

2.4   Effect on wellbeing

The impacts of the crowding phenomenon on passengers' health and wellbeing is extremely complex to analyse. Attached to the discomfort of sharing a limited space with several people are multiple physical and psychological factors that intervene in the perception of crowding and its effects. Amongst the reasons for the aversion of public transport users to waiting and travelling in crowded conditions, we can name increased anxiety (Cheng, 2010), stress and feeling of exhaustion (Lundberg, 1976; Mohd Mahudin *et al.*, 2011; 2012), perceptions of risk to personal safety and security (Cox *et al.*, 2006; Katz and Rahman, 2010)[2], feelings of invasion of privacy (Wardman and Whelan, 2011), propensity to arrive late at work (Mohd Mahudin *et al.*, 2011) and a possible loss in productivity for passengers that work while sitting on a train (Fickling *et al.*, 2008; Gripsrud and Hjorthol, 2012).

Empirical evidence to substantiate the negative effects of crowding on public transport users is still limited but growing. Lundberg (1976) measured the rate of catecholamine excretion in urine for rail commuters in Sweden and found that feelings of discomfort (related to catecholamine excretion) grew more intense as the number of train passengers increased. More recently Cantwell *et al.* (2009) find that crowding is a significant source of dissatisfaction for public transport users in Ireland, by using a stated choice experiment in which respondents had to choose between rail and bus alternatives with different levels of crowding. The result of Cantwell *et al.* (2009) is reinforced by Cheng (2010), who finds by means of a psychometric method - the Rasch model - that crowding is the factor that causes the most anxiety in rail commuters in Taiwan (ranked on top of "delays", accessibility to a railway station, searching for the right train on a platform, and need of transfers).

Besides anxiety and stress, other symptoms have also been found to be related to high levels of crowding. Using data from Kuala Lumpur, Mohd Mahudin *et al.* (2011) found that commuters with greater levels of stress and exhaustion attributed to crowding, reported more somatic symptoms like headaches, tension, stiff muscles and sleeplessness. The

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[2] Cox et al. (2006) suggest that the relationship between crowding and personal security may be contingent upon crime type, as a crowded environment may discourage muggings, but at the same time make easier pick pocketing and verbal and physical abuse.

propensity to be late at work is found to be a spillover effect of rail crowding, in cases in which passengers have to let an overcrowded train pass (or decide to do so in hope that the next train will be less crowded, sometimes unsure of the exact time the next train will arrive).

Mohd Mahudin *et al.* (2012) present the most comprehensive empirical study on the psychological dimensions of rail crowding to date. The experience of passenger crowding is characterised by three different psychological components: (*i*) evaluation of the psychosocial aspects of the crowded situation (including the items *unpleasant*, *disturbing*, *cluttered*, *chaotic*, *dense*, *disorderly* and *confining*); (*ii*) evaluation of the ambient environment of the crowded situation (including the items *hot*, *smelly*, *stuffy* and *noisy*); and (*iii*) affective reactions to the crowded situation (including the items *irritable*, *frustrated*, *tensed*, *distracted*, *stressful*, *hindered*, *restricted*, *uncomfortable* and *squashed*). Each item is given a score by respondents concerning its linkage to the crowding experience. It is found that commuters' evaluations of the psychosocial aspects of the crowded situation (*i* above) and of its ambient environment (*ii* above), together with their rating of passenger density can predict affective reactions to the crowded situation (*iii* above); that the affective reactions (*iii* above) significantly predict stress and feelings of exhaustion; and that evaluations of the psychosocial aspects of the crowded situation (*i* above) and of its ambient environment (*ii* above) as well as passenger density do not directly predict stress and feelings of exhaustion. Therefore, the authors conclude that the link between rail passenger crowding and the negative outcomes is mediated by affective feelings of crowdedness.

All in all, we can conclude that the existing empirical data and related models show the detrimental effect of crowding on travelling comfort and general wellbeing, which in turn is expected to influence travel decisions such as mode, route and departure time. The inclusion of crowding in formal demand modelling is discussed in the next section.

2.5   Effect on the valuation of travel time savings

The crowding cost, crowding externality or crowding penalty that is likely to arise in some way as the occupancy levels of vehicles or transfer stations increase, make passengers willing to pay more to reduce their travel time if, for example, they travel in a bus with an average occupancy of four passengers per square metre, than in the case in which a bus has a few passengers, all comfortably seated. Then, a relationship between density and the value of travel time savings (VTTS) is expected to exist, as empirically found by Maunsell and Macdonald (2007), Whelan and Crockett (2009) and Hensher *et al.* (2011) among others, who estimate discrete choice models using stated choice data[3]. Moreover, the impact of passengers' density on the disutility of travelling is unlikely to be linear as an extra passenger per bus or train does not impose the same cost on everyone else when the occupancy level is 20 or 95 percent (measured against total capacity).

A usual outcome of discrete choice models that include a crowding parameter on the valuation of in-vehicle travel time savings is the estimation of a "crowding multiplier", i.e., a factor that multiplies the value of in-vehicle time savings found under uncrowded conditions, which increases in value as crowding worsens. The estimation of crowding

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[3] For recent reviews of crowding valuation studies, including the representation of crowding in stated choice experiments, see Wardman and Whelan (2011) and Li and Hensher (2011).

multipliers under several travel conditions has received considerable attention in the rail industry in Britain (Wardman and Whelan, 2011). For example, Whelan and Crockett (2009) estimated the crowding multiplier for rail services as a function of either the load factor (defined as the total number of passengers inside a vehicle, over the seating capacity) or the number of passengers standing per square metre. The results for the latter case are quite illustrative, as shown in Figure 1.
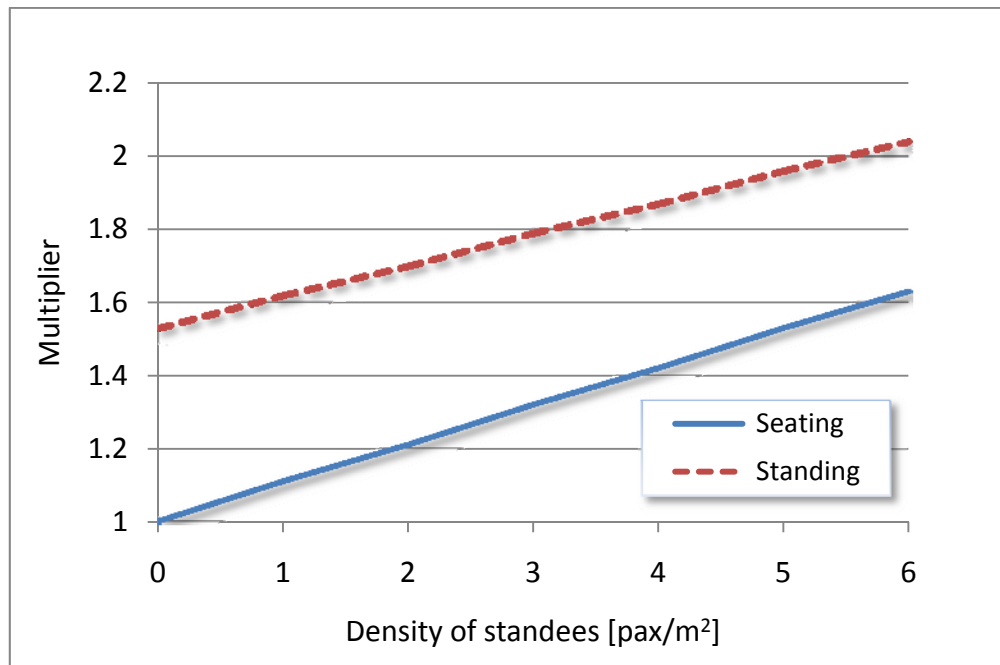

Figure 1: Crowding multiplier for passengers sitting and standing
(own elaboration from Whelan and Crockett, 2009)

For passengers sitting, the crowding multiplier increases from 1.0 to 1.63 as the density of standing passengers increases from zero to six passengers per square metre, whereas for passengers standing these figures are 1.53 and 2.04, respectively. Figure 1 confirms intuition, as passengers standing have a higher willingness to pay to reduce travel time than passengers sitting (when the former have not chosen to stand, but rather have to do it because all seats are taken), and the discomfort of travelling of passengers sitting and standing increases with the number of standees. Moreover, Wardman and Whelan (2011) review a number of rail crowding valuation studies in Britain, and find that the crowding effect is usually activated from load factors between 60 and 90 percent onwards (although even lower load factors may be a source of crowding for leisure travellers), a result that the authors relate to the loss of personal space and the inability of groups to seat together that occur when more than a threshold percent of seats are occupied, even before passengers have to stand. The crowding discomfort is found to be higher for leisure travellers than for commuters.

Finally, in busy public transport systems, passengers may not only be affected by crowding effects while travelling aboard vehicles, but also on accessways, transfer areas, waiting areas and platforms, a phenomenon that could also affect the experience of accessing a public transport service or waiting for a vehicle. The effect of crowding at train stations on increasing the discomfort of travellers has been estimated by Lam *et al.* (1999) for Hong Kong and Douglas and Karpousis (2005) for Sydney; in the latter study a relationship

between the value of waiting time savings and different levels of crowding on train stations is estimated.

2.6   Effect on route and bus choice

The disutility of standing aboard public transport vehicles may influence bus and route choice when passengers have multiple alternatives to complete a trip. This has been recently incorporated into public transport assignment models such as Sumalee *et al.* (2009), Leurent and Liu (2009), Hamdouch *et al.* (2011) and Schmöcker *et al.* (2011), who estimate the probability of getting a seat both when boarding a bus, and once on board if a passenger has to stand at the beginning of his/her trip. Passengers choose departure time and route according to their perceived travel disutility, which includes the probability of getting a seat (or failure to do so) as a key attribute.

Numerical applications show that perceived seat availability may have a significant influence on departure time, route choice and bus choice. For example, Leurent and Liu (2011) find that the predicted passenger load in the Paris metro is reduced by around 30 percent when applying a model with different seat/stand disutilities, relative to a model that does not distinguish sitting from standing. Raveau *et al.* (2011) show that the occupancy rate of trains is significant in explaining route choice in the metro network of Santiago de Chile, and that the effect is non-linear; it increases for very high occupancy rates when users perceive that, apart from the discomfort effect of crowding, there are higher chances of not being able to board the first train (Section 2.2). Kim *et al.* (2009) use stated choice data from Seoul to estimate the probability of passengers waiting for a second bus if they are provided with real time information on the occupancy level of the next bus arriving at a bus stop; with results showing that the availability of seats increases the probability of a passenger to choose boarding an arriving bus. In other words, up to a point, some passengers are willing to trade waiting time for an (expected) higher chance of getting a seat while travelling.

2.7   Effect on optimal public transport supply and fare

Crowding as a factor that affects the users' utility and generalised cost of travelling has been recognised by several authors in the analysis of public transport pricing and supply policy (Jansson, 1979; Kraus, 1991; Jansson, 1993; Arnott and Yan, 2000; Huang, 2002; Pedersen, 2003; Pels and Verhoef, 2007; Parry and Small, 2009). The basic idea is that when a person boards a bus or a train, they may impose a crowding externality on everyone else on board, which is especially noticeable when there are passengers standing. Therefore, the crowding externality raises the marginal social cost of travelling, thus increasing the optimal bus or rail fare, which is obtained as the difference between total marginal cost and average users cost on first best pricing (see, e.g., Tisato, 1998; Jara-Díaz and Gschwender, 2005).

In the economic literature of public transport, it is usually proposed that when users' waiting time cost is included in the total cost function of public transport services, the marginal cost pricing rule does not cover operator cost due to the positive effect of increasing frequency in reducing waiting time for users (Mohring, 1972; Turvey and Mohring, 1975; Jansson, 1979).

This is a common result obtained from a number of bus pricing and optimisation studies along the lines of Mohring (1972)'s well-known square root formula, which states that an increase in demand is optimally met by a less than proportional increase in supply. Therefore, as demand grows there is an increase in the occupancy rate or load factor inside vehicles, that is, an increase in density, and possibly, crowding effects. Consequently, it is reasonable to analyse what would happen if a crowding disutility is considered in the frequency and fare optimisation problem.

The first answer to this problem is provided by Kraus (1991), who considered the standing externality that long-distance passengers who are able to find an empty seat, impose upon short-distance passengers that have to stand because all seats are taken by long-distance passengers. This issue should be translated into a higher optimal fare for long-distance travellers. Kraus (1991) assumes that the value of in-vehicle time savings (P_v) is higher for standees than for passengers sitting due to the discomfort caused by standing. A similar approach is introduced by Jara-Díaz and Gschwender (2003), who demonstrate that the optimal bus frequency is higher if P_v is a linear function of the average occupancy rate of a bus, relative to the case in which there is no crowding externality reflected on P_v.

The inclusion of crowding externality in public transport optimisation models has also been shown to seriously challenge frequency-related total cost savings (scale economies). When the disutility of crowding is accounted for as increasing P_v, average total cost could pass from a decreasing function of demand for low to middle demand levels, to an increasing function of demand for middle to high demand levels, as shown by Tirachini *et al.* (2010b) with a frequency optimisation model on a single public transport route. This result is due to the increase in density when demand rises, which (in a model that takes crowding into account) is translated into an increase of users in-vehicle time cost. However, the result of a crowding-induced increasing total cost for a single route vanishes if the number of routes is also an optimisation variable, in which case route density is adjusted to keep total costs down (Tirachini *et al.*, 2010a).

In summary, the acknowledgement of a crowding externality on the valuation of travel time and on travel time itself might have significant effects on the design of a public transport system, particularly in terms of the capacity provided to serve demand. When the crowding cost is ignored, policy makers may choose to provide a transport capacity that is just enough to meet demand, in which buses would be full (or close to full if a safety level of spare capacity is defined by design) in the most loaded sections of a route. Nevertheless, when the crowding cost is considered in the design stage of a route, it should be optimal to provide a greater service frequency and bus capacity in order to reduce the occupancy levels inside vehicles, and consequently improve the quality of travelling (Jara-Díaz and Gschwender, 2003). This issue will be revisited in the next section with new crowding cost functions that depend on the load factor of public transport vehicles, and that account separately for the proportion of users seated and the density of standees inside vehicles.

3.   Estimation of Crowding and Standing Costs

3.1 Data description

Section 2 discussed several dimensions of the influence of having a large number of passengers inside public transport vehicles and stations. In particular, Section 2.5 referred to previous studies that estimate crowding and standing costs as increasing the valuation of travel time savings. In this section we estimate mode choice models that include the proportion of available seats and the density of standees as attributes. We have two aims: (i) to show differences in the estimation of in-vehicle travel time savings (VTTS) of including or ignoring crowding as a source of disutility for public transport users, and (ii) to analyse the implications of different crowding cost specifications for the estimation of VTTS.

The data set used for the estimation of choice models is part of a feasibility study for a new metro system proposed for Sydney, conducted in 2009 by the Institute of Transport and Logistics Studies at The University of Sydney (Hensher *et al.*, 2011). The modes included are car, bus, train and metro. In the stated choice experiment, respondents compare the levels of access and in-vehicle times, frequency, proportion of users sitting and number of users standing, and costs (e.g., public transport fare, running cost and parking fee for cars). We have used a sub-set of the commuter and non-commuter data set where the choice was (i) between the current bus and the proposed metro, or (ii) between car and metro. Full details on the experiment design, study area, sample size and socioeconomic characteristics of respondents are described at length in Hensher *et al.* (2011). The crowding variable in the choice experiment is not pivoted around the respondent's experience in using a public transport mode, or even their perceptions of levels of crowding, if the mode is an alternative to the actual model chosen in a recent trip.

Crowding levels on bus, train and metro were represented with diagrams, two examples of different levels of bus and train crowding are shown in Figure 2 (in line with the combinations of attribute levels identified in a D-optimal design, see Rose *et al.*, 2008). The pictorial displays of the number of people sitting and standing in each mode is from above (i.e., a bird's eye view), which is a common representation in the few stated choice studies that have considered crowding. We acknowledge that in reality people boarding a bus or a train will not see it in this way, but rather with a vertical snapshot of the situation as they board the vehicle or when they see it arriving at the station, as the three-dimensional representations used by Fröhlich *et al.* (2012). We are unable to consider this perspective, but it raises an important question as to how individuals perceive the degree of crowding and is worth investigating in future research.
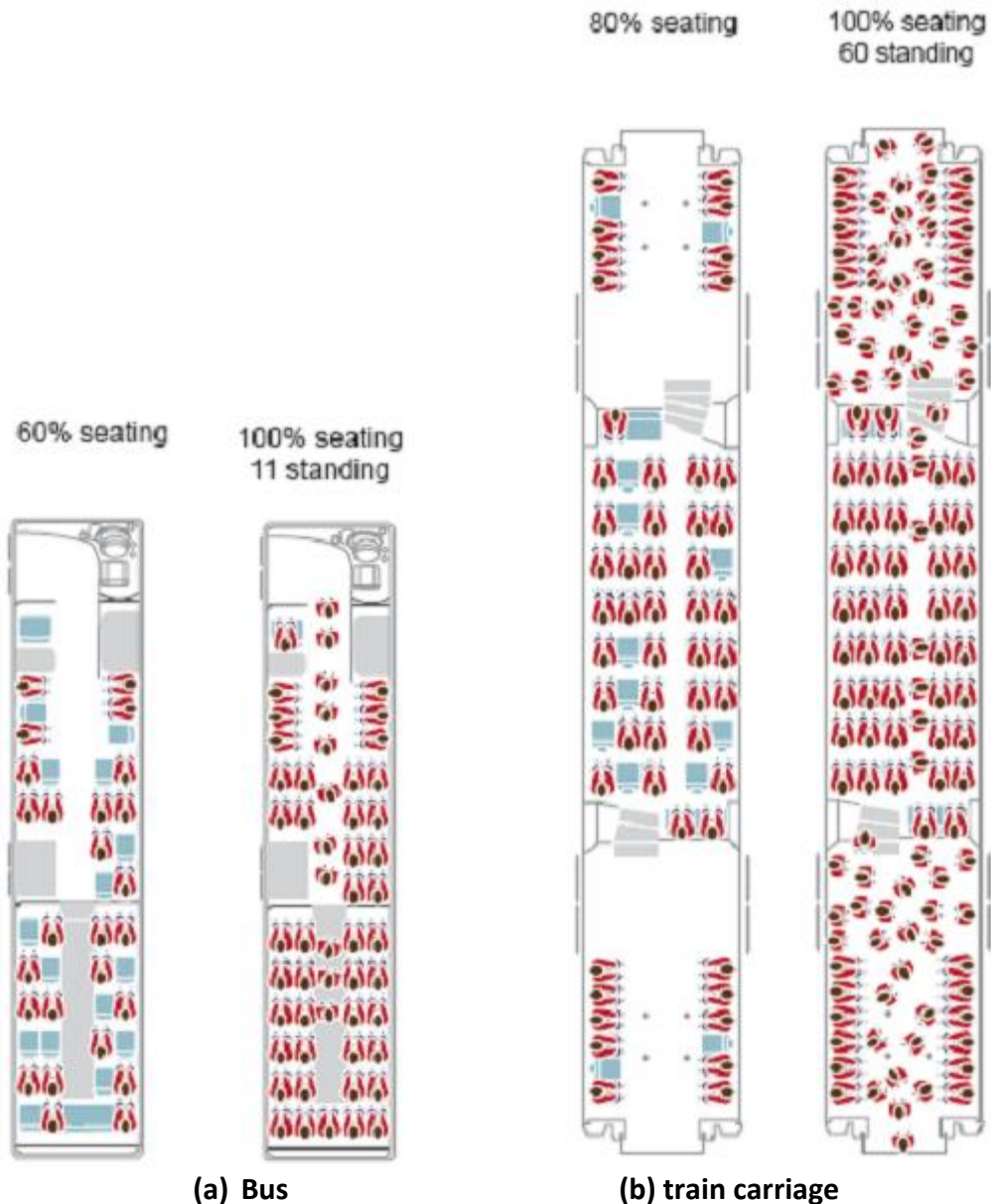
(a) Bus   (b) train carriage

Figure 2: Different levels of occupancy in stated preference study
(source: stated preference model described in Hensher *et al.*, 2011)

Hensher *et al.* (2011) estimate the crowding disutility as a function of the proportion of users sitting (which affects the probability of getting a seat), and the number of users standing, in order to estimate the willingness to pay to get a seat as a function of the number of people sitting and standing. In this work we use the density of standees per square metre -instead of the number of standees- to represent the disutility of crowding and standing, in order to have a common base among the three public transport modes considered, which have different sizes and proportion of area for sitting and standing (for example, in Figure 2 the train has proportionally more space allocated to standing than the bus). Crowding models that depend on the occupancy level or load factor (number of passengers over number of seats) are also estimated, as it is more common in the literature.

Multinomial logit (MNL) and Error Components (EC) models are estimated in this section.. In order to compare values of VTTS and crowding multipliers, we propose five different utility specifications: four models that incorporate attributes representing the number of

passengers sitting and standing, interacting with travel time; which will be compared with one specification that ignores any crowding or standing cost. Defining V_m as the utility of mode m, the five cases, named M1 to M5, are described as follows:

- M1: No crowding cost (eq. 1).
- M2: Only the density of standees [pax/m^2] imposes an extra discomfort cost (eq. 2).
- M3: The density of standees and the proportion of seats occupied are sources of disutility (eq. 3). In the survey, the minimum proportion of seats occupied is 25 percent.
- M4: The crowding disutility arises when the load factor reaches 60 percent (eq. 4).
- M5: The crowding disutility arises when the load factor reaches 90 percent (eq. 5).

$$V_m = \alpha_m^{M1} + \beta_a^{M1} t_{am} + \beta_h^{M1} h_m + \beta_v^{M1} t_{vm} + \beta_e^{M1} t_{em} + \beta_c^{M1} c_m \tag{1}$$

$$V_m = \alpha_m^{M2} + \beta_a^{M2} t_{am} + \beta_h^{M2} h_m + \beta_v^{M2} t_{vm} + \beta_e^{M2} t_{em} + \beta_c^{M2} c_m + \beta_{den\,m}^{M2} n_{den\,m} t_{vm} \tag{2}$$

$$V_m = \alpha_m^{M3} + \beta_a^{M3} t_{am} + \beta_h^{M3} h_m + \beta_v^{M3} t_{vm} + \beta_e^{M3} t_{em} + \beta_c^{M3} c_m + \beta_{den\,m}^{M3} n_{den\,m} t_{vm} + \tag{3}$$

$$+ \beta_{seat} \max\left(p_{seat\,m} - 0.25, 0\right) t_{vm}$$

$$V_m = \alpha_m^{M4} + \beta_a^{M4} t_{am} + \beta_h^{M4} h_m + \beta_v^{M4} t_v + \beta_e^{M4} t_{em} + \beta_c^{M4} c_m + \beta_{lf\,60m} \max\left(lf_m - 0.6, 0\right) t_{vm} \tag{4}$$

$$V_m = \alpha_m^{M4} + \beta_a^{M4} t_{am} + \beta_h^{M4} h_m + \beta_v^{M4} t_{vm} + \beta_e^{M4} t_{em} + \beta_c^{M4} c_m + \beta_{lf\,90m} \max\left(lf_m - 0.9, 0\right) t_{vm} \tag{5}$$

Models M2 to M5 assume different levels for the minimum occupancy rate that triggers a crowding effect for passengers, from 25 percent in M3 to 100 percent in M2, passing through 60 and 90 percent in M4 and M5, respectively[4]. In general, the true crowding threshold on occupancy level is context dependent, given by cultural and idiosyncratic characteristics of the users, and on the other hand, by the design and operation of vehicles. Therefore, it is timely to analyse how different level of sensitivity to the level of seats occupied reflect on the valuation of travel time savings, and ultimately on demand prediction.

In equations (1) to (5), t_{am} and t_{em} are the access and egress times, respectively, h_m is the headway between two consecutive vehicles (representing a proxy for waiting time cost), t_{vm} is in-vehicle time, c_m the money cost (fare in the case of public transport modes), $n_{den\,m}$ the density of standees per square metre, p_{seat} the proportion of seats that are occupied, lf_m is the load factor, α_m is a mode specific constant (MSC), and β_k are the parameters

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[4] This is based on the analysis of Wardman and Whelan (2011), who review seventeen crowding valuation studies in British trains. The crowding effect is usually activated from load factors between 60 and 90 percent onwards (although even lower load factors may be a source of crowding for leisure travellers). With our database, models estimated assuming threshold load factors between 50 and 100 percent did not produce significant differences on goodness-of-fit, therefore two models, assuming 60 percent (M4) and 90 percent (M5) thresholds are chosen for illustration and analysis of effects.

associated with the different attributes. For each model (M1 to M5), the utility of the alternative car mode (d) has the same specification: $V_d = \beta_a^{M.} t_{ad} + \beta_{vd}^{M.} t_{vd} + \beta_e^{M.} t_{ed} + \beta_{cd}^{M.} c_d$.

3.2 Multinomial Logit model

The estimation of parameters and specification (likelihood ratio) tests are presented in Table 1 (n=4152 observations). Estimation is made with the program NLogit5.

Table 1: Estimation of parameters, MNL models

Parameter	M1	M2	M3	M4	M5
Access time β_a	-0.020 (-3.14)	-0.016 (-2.48)	-0.015 (-2.40)	-0.015 (-2.41)	-0.016 (-2.48)
Headway β_h	-0.009 (-4.29)	-0.011 (-4.91)	-0.010 (-4.83)	-0.010 (-4.85)	-0.011 (-4.92)
Travel time PT β_v	-0.019 (-7.85)	-0.014 (-5.75)	-0.008 (-2.59)	-0.011 (-4.50)	-0.014 (-5.67)
Egress time β_e	-0.044 (-6.30)	-0.045 (-6.34)	-0.045 (-6.42)	-0.045 (-6.40)	-0.045 (-6.34)
Fare β_c	-0.153 (-6.50)	-0.147 (-6.18)	-0.148 (-6.23)	-0.148 (-6.22)	-0.148 (-6.20)
Travel time car β_v	-0.023 (-6.72)	-0.024 (-6.98)	-0.024 (-6.98)	-0.024 (-6.98)	-0.024 (-6.98)
Car cost β_c	-0.039 (-5.71)	-0.041 (-5.90)	-0.041 (-5.88)	-0.041 (-5.90)	-0.041 (-5.90)
MSC train α_t	-4.004 (-4.69)	-4.185 (-4.91)	-4.199 (-4.92)	-4.214 (-4.94)	-4.187 (-4.91)
MSC metro α_m	-3.146 (-3.79)	-3.121 (-3.77)	-3.138 (-3.79)	-3.127 (-3.77)	-3.123 (-3.77)
MSC bus α_b	-2.666 (-3.27)	-2.675 (-3.29)	-2.661 (-3.27)	-2.681 (-3.29)	-2.679 (-3.29)
Travel time* Density standees train β_{dent}		-0.0019 (-1.92)	-0.001 (-0.73)		
Travel time* Density standees metro β_{denm}		-0.0065 (-7.17)	-0.005 (-5.26)		
Travel time* Density standees bus β_{denb}		-0.0026 (-3.46)	-0.002 (-2.43)		
Travel time* Proportion seats β_{seat}			-0.012 (-2.46)		
Travel time* load factor train $\beta_{lf\,t}$				-0.010 (-2.60)	-0.012 (-2.04)
Travel time* load factor metro $\beta_{lf\,m}$				-0.016 (-7.54)	-0.018 (-7.32)

Travel time* load factor bus $\beta_{lf\,b}$				-0.006 (-4.00)	-0.006 (-3.49)
Specification tests					
Log-likelihood	-2922.3	-2888.5	-2885.5	-2885.7	-2887.3
Adjusted ρ^2 (relative to ASCs)	0.0950	0.1045	0.1052	0.1054	0.1049
Likelihood ratio test with respect to M1		67.57 ($> \chi_{3,0.001}$ =16.27)	73.59 ($> \chi_{4,0.001}$ =18.47)	73.24 ($> \chi_{3,0.001}$ =16.27)	69.92 ($> \chi_{3,0.001}$ =16.27)
Likelihood ratio test with respect to M2			6.01 ($> \chi_{1,0.025}$ =5.02)		

Note: *t*-ratio in bracket below parameter estimates. Time is in minutes, cost is in $ (2009 AUD).

Focusing on the goodness-of-fit measures, the log-likelihood and adjusted ρ^2 statistics relative to a model with alternative specific constants (ASCs) only, demonstrate that the four crowding models (M2-M5) outperform the model with no crowding variables (M1). A likelihood ratio test indicates that M2, M3, M4 and M5 are significantly superior to M1 at the 99.9 percent confidence level. The adjusted ρ^2 values are between 0.1045 and 0.1054 for the crowding models, with the models that assume a crowding effect at low occupancy levels (25 percent in M3 and 60 percent M4) providing a slightly superior value, relative to M1 (100 percent threshold) and M4 (90 percent threshold). A likelihood ratio test between nested models M2 and M3 indicates that M3 is superior at the 97.5 percent confidence level, which suggests that the density of standees alone is not enough to properly account for the disutility of crowding; rather the availability of seats also plays a role in the choices made by respondents.

Figure 3 shows the value of in-vehicle time savings (VTTS), for the five estimated models, as a function of the load factor (occupancy rate) and density of standees. The train (Figure 2b) is chosen for illustration; conclusions are the same for the other two public transport modes (bus and metro). In each train car there are 82 seats and a maximum of 120 standees, which corresponds to 4.4 standees per square metre and a load factor of 2.46 at crush capacity. In general, the model that is indifferent to the occupancy levels of vehicles overestimates VTTS for low load factors (below a threshold that is between 1.0 and 1.25, depending on the crowding model) and underestimates VTTS for high load factors (over 1.25). At this point it is worth noting that the VTTS for M1, 7.2 $/h (for all three public transport modes), may be biased because M1 is estimated ignoring the influence of crowding (Figure 2) in the respondent's choices. However, the average value 7.2 $/h of M1 fall within the confidence intervals found by Hensher *et al.* (2011), who using an Error Components model over the same dataset, obtained an average VTTS of 7.7 $/h for bus and 8.6 $/h for train and metro, with 95 percent confidence intervals of (4.9, 12.3) for bus and (5.6, 12.1) for train and metro.

For the crowding-sensitive models, Figure 3 shows that the different assumptions concerning the threshold load factor that triggers a crowding effect (from 25 percent in M3

to 100 percent in M2) do have an influence on the resulting willingness to pay outputs, but this effect is more noticeable for low occupancy levels. Indeed, the alternative crowding models predict quite different VTTS if the load factor is below 1.0 or 1.5; however, for higher crowding levels all models tend to estimate similar VTTS. In other words, if a system is operated in highly crowded conditions, it makes little difference how sensitive people are to crowding when everyone is sitting.
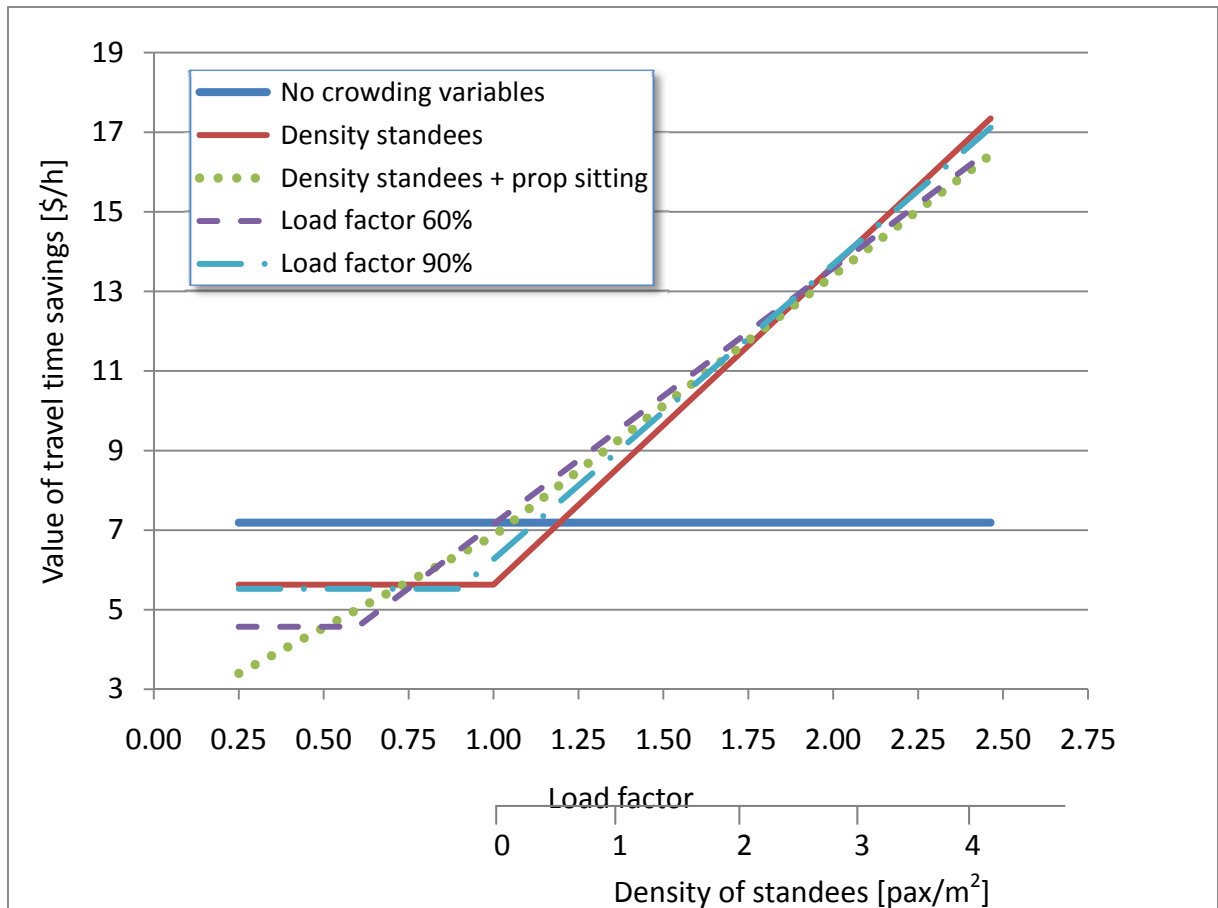

Figure 3: Value of in-vehicle time savings, MNL models

Confidence intervals for the value of in-vehicle time savings, for increasing levels of crowding inside vehicles are given in Figure 4. We take M4 (minimum load factor that triggers a crowding effect is 60 percent) for illustration, and calculate 95 percent confidence intervals using the Delta method for non-linear utility functions (Rose *et al.*, 2012). The range of values that is likely to include the true value of in-vehicle time savings widens as crowding levels increase. For a given load factor, the variation around the mean estimate of in-vehicle travel time savings is ±$2/hour at low load factors to ±$5/hour at high load factors.
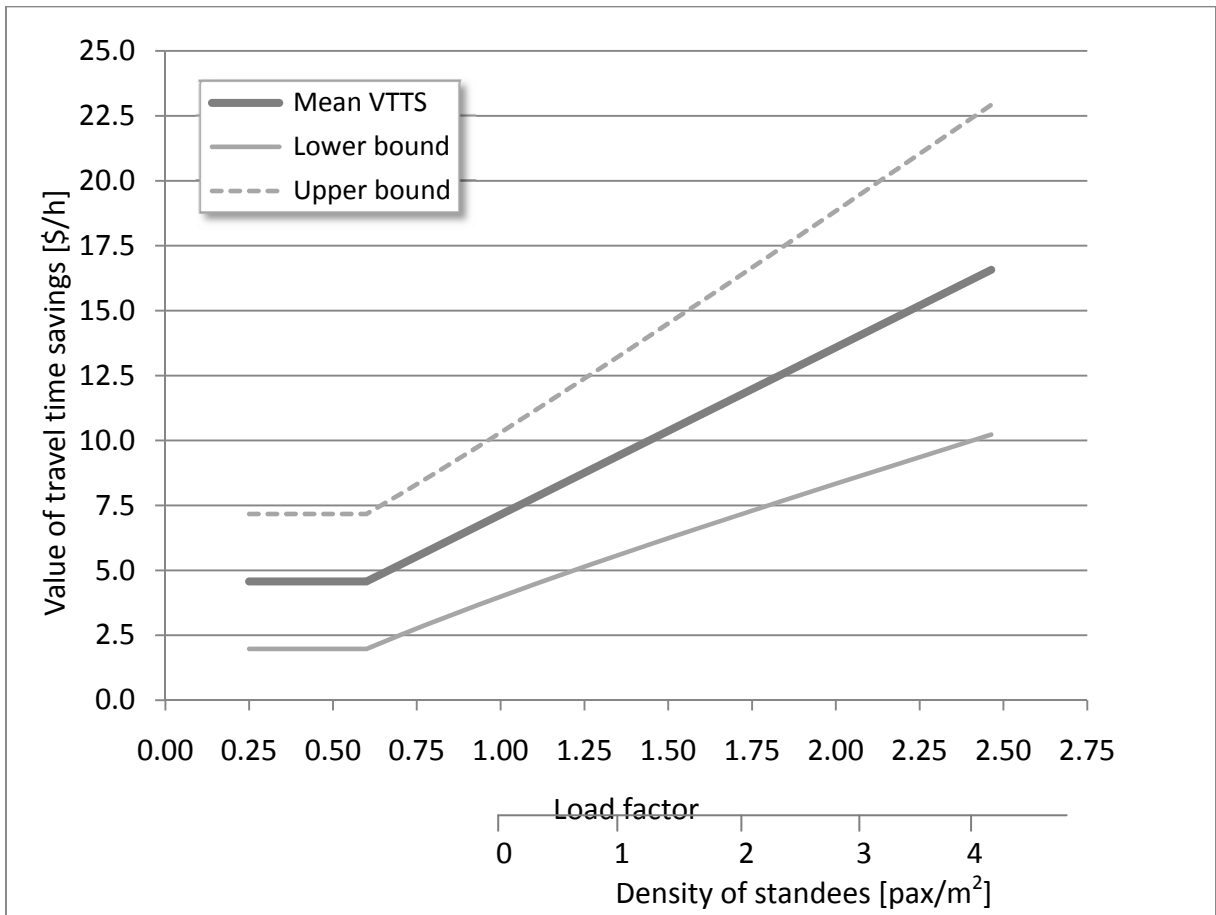
Figure 4: Confidence intervals, value of in-vehicle time savings M4

Next, we analyse the crowding multiplier that arises from the values in Figure 3. The crowding multiplier is the mark-up on the VTTS induced by crowding conditions, compared against uncrowded travel conditions. Figure 5 shows that crowding multipliers are very sensitive to the alternative crowding disutility specifications, with values between 3 and 4.8 at crush capacity. Compared to the extant literature, Whelan and Crocket (2009) found that the crowding effect is active at a 0.9 load factor, with crowding multipliers that scale up to 1.8 for sitting and 2.4 for standing when the load factor is 2, assumed to be the maximum load factor for trains in Britain (equal number of passengers sitting and standing). In our model with a 0.9 load factor threshold (M5), the crowding multiplier is 2.0 (average for sitting and standing) when the load factor is 2. This crowding multiplier is within the range of crowding multipliers for sitting and standing found by Wardman and Whelan (2011) in a meta-analysis of British crowding valuation studies.
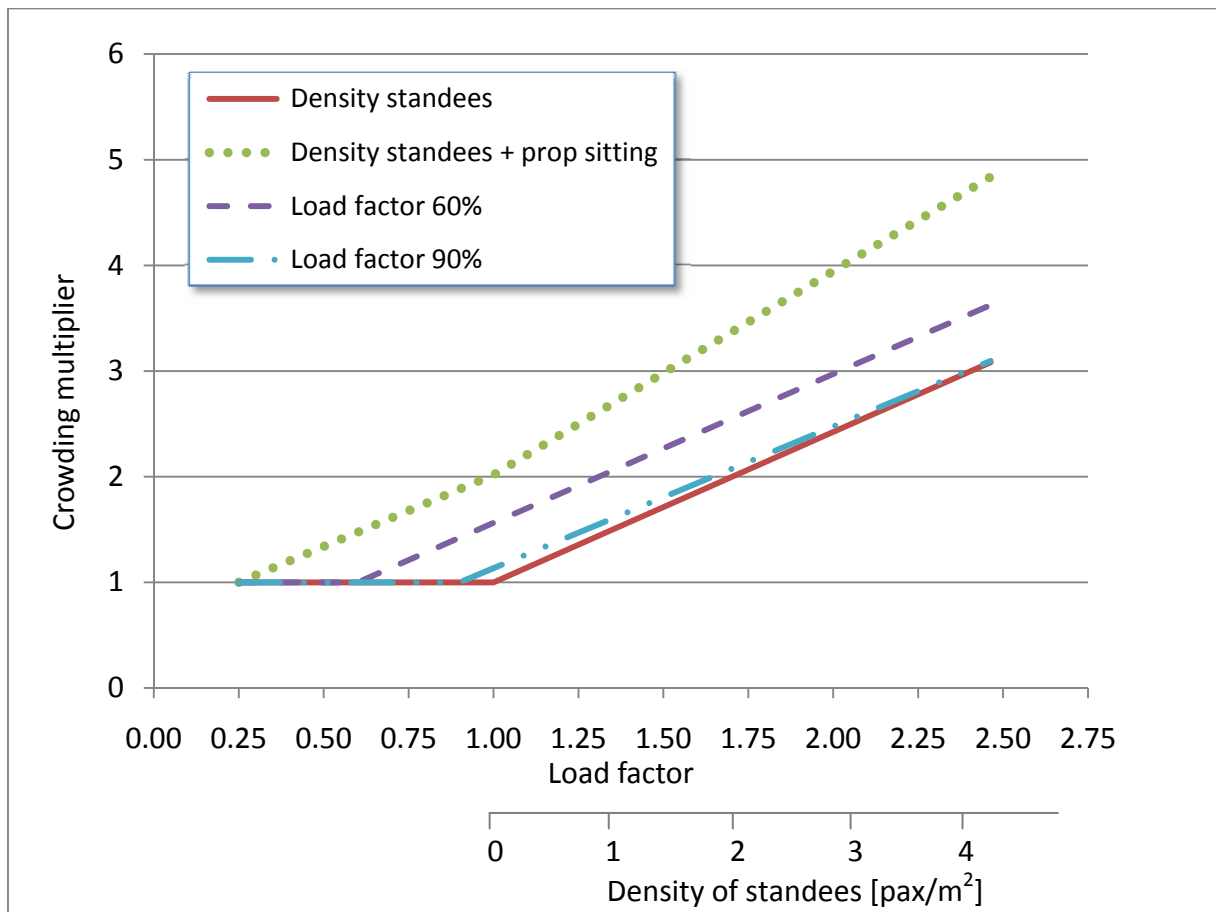
Figure 5: Crowding multiplier, MNL models

3.3 Error Components model

An Error Components (EC) logit model is estimated to account for the panel nature of the data (in the survey, there are six choice scenarios for each respondent) and the correlated structure on common-respondent observations. Like a Nested Logit (NL) model, an EC model allows for degrees of similarity between subsets of modal alternatives, and additionally, an EC model has the advantage of taking into account the pseudo panel nature of stated choice data. Therefore, the model outputs may be used in the same way as those obtained from a NL model; however the parameters obtained from an EC model are less likely to be biased as a result of respondents completing more than one choice task[5]. In the formulation of the EC model, the marginal probability of observing a sequence of choices is modelled, which is done through simulation over the random parameters and error terms. This simulation requires that draws be taken over the random parameter (and/or error component) distribution space. To ensure coverage of the entire space of the parameter distributions, quasi-random Monte Carlo methods are usually used by modellers. In the models reported below, we used 500 Halton draws in a simulated log-likelihood function. Estimation is made with the program NLogit5.

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[5] For a full description and derivation of the EC model, see, e.g., Train (2003), Hensher *et al.* (2005, 2011).

Table 2: Estimation of parameters, EC models

Parameter	M1	M2	M3	M4	M5
Access time β_a	-0.042 (-2.74)	-0.035 (-2.24)	-0.034 (-2.22)	-0.034 (-2.19)	-0.035 (-2.24)
Headway β_h	-0.013 (-4.94)	-0.016 (-5.90)	-0.016 (-5.90)	-0.016 (-5.91)	-0.016 (-5.93)
Travel time PT β_v	-0.040 (-7.85)	-0.032 (-7.96)	-0.024 (-4.59)	-0.028 (-6.78)	-0.032 (-7.90)
Egress time β_e	-0.068 (-4.72)	-0.071 (-4.84)	-0.074 (-4.97)	-0.073 (-4.89)	-0.072 (-4.85)
Fare β_c	-0.312 (-7.64)	-0.319 (-7.89)	-0.325 (-8.00)	-0.328 (-7.96)	-0.320 (-7.93)
Travel time car β_v	-0.041 (-4.99)	-0.043 (-5.16)	-0.043 (-5.16)	-0.044 (-5.21)	-0.043 (-5.16)
Car cost β_c	-0.121 (-5.71)	-0.124 (-7.95)	-0.124 (-7.94)	-0.125 (-7.98)	-0.124 (-7.95)
MSC train α_t	-6.478 (-0.93)	-6.730 (-1.00)	-6.759 (-1.00)	-6.821 (-1.02)	-6.722 (-1.00)
MSC metro α_m	-5.147 (-0.74)	-5.139 (-0.76)	-5.183 (-0.77)	-5.233 (-0.78)	-5.138 (-0.76)
MSC bus α_b	-4.547 (-0.66)	-4.495 (-0.67)	-4.502 (-0.67)	-4.577 (-0.68)	-4.494 (-0.67)
Travel time* Density standees train β_{dent}		-0.0036 (-2.73)	-0.002 (-1.31)		
Travel time* Density standees metro β_{denm}		-0.0094 (-8.72)	-0.008 (-5.99)		
Travel time* Density standees bus β_{denb}		-0.0045 (-2.72)	-0.003 (-2.05)		
Travel time* Proportion seats β_{seat}			-0.018 (-2.56)		
Travel time* load factor train $\beta_{lf\,t}$				-0.019 (-3.47)	-0.022 (-2.74)
Travel time* load factor metro $\beta_{lf\,m}$				-0.023 (-9.10)	-0.026 (-8.84)
Travel time* load factor bus $\beta_{lf\,b}$				-0.011 (-3.17)	-0.010 (-2.72)
Error Components					
Bus, Car	1.596 (6.60)	1.516 (6.07)	1.499 (5.98)	1.507 (5.82)	1.514 (6.07)
Bus, Train	1.870 (15.38)	1.934 (15.80)	1.943 (15.79)	1.932 (15.61)	1.933 (15.80)
Bus, Train, Metro	-2.381 (-6.68)	-2.491 (-7.12)	-2.506 (-7.17)	-2.540 (-7.14)	-2.493 (-7.14)
Specification tests					
Log-likelihood	-2417.7	-2380.3	-2376.733	-2376.6	-2379.6

Adjusted ρ² (relative to ASCs)	0.250	0.260	0.261	0.262	0.261

Analogous to the value of in-vehicle time savings (Figure 3) and crowding multipliers (Figure 5) obtained from the estimation of MNL models, Figures 6 and 7 show VTTS and crowding multipliers from the EC models of Table 2. Some changes in the absolute values of VTTS estimated with EC and MNL models are evident, for example, the EC models estimate a smaller VTTS than the MNL models with high crowding levels, which is translated into lower crowding multipliers in Figure 7 with respect to Figure 5; however, the shape and relative order of the figures do not change as a function of the choice model assumed, and therefore, the same conclusions about the implications of alternative formulations for the crowding cost, made with MNL models, are valid with the more general EC models estimated.
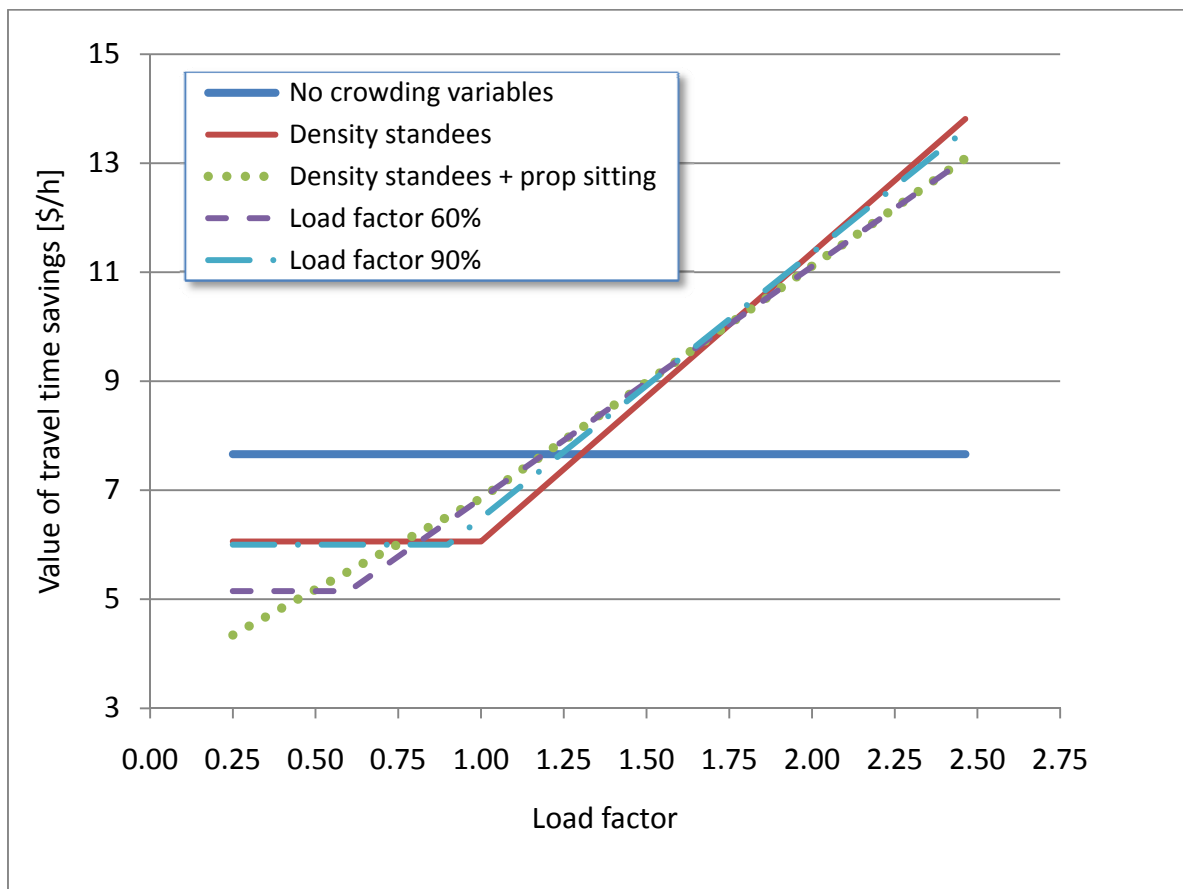

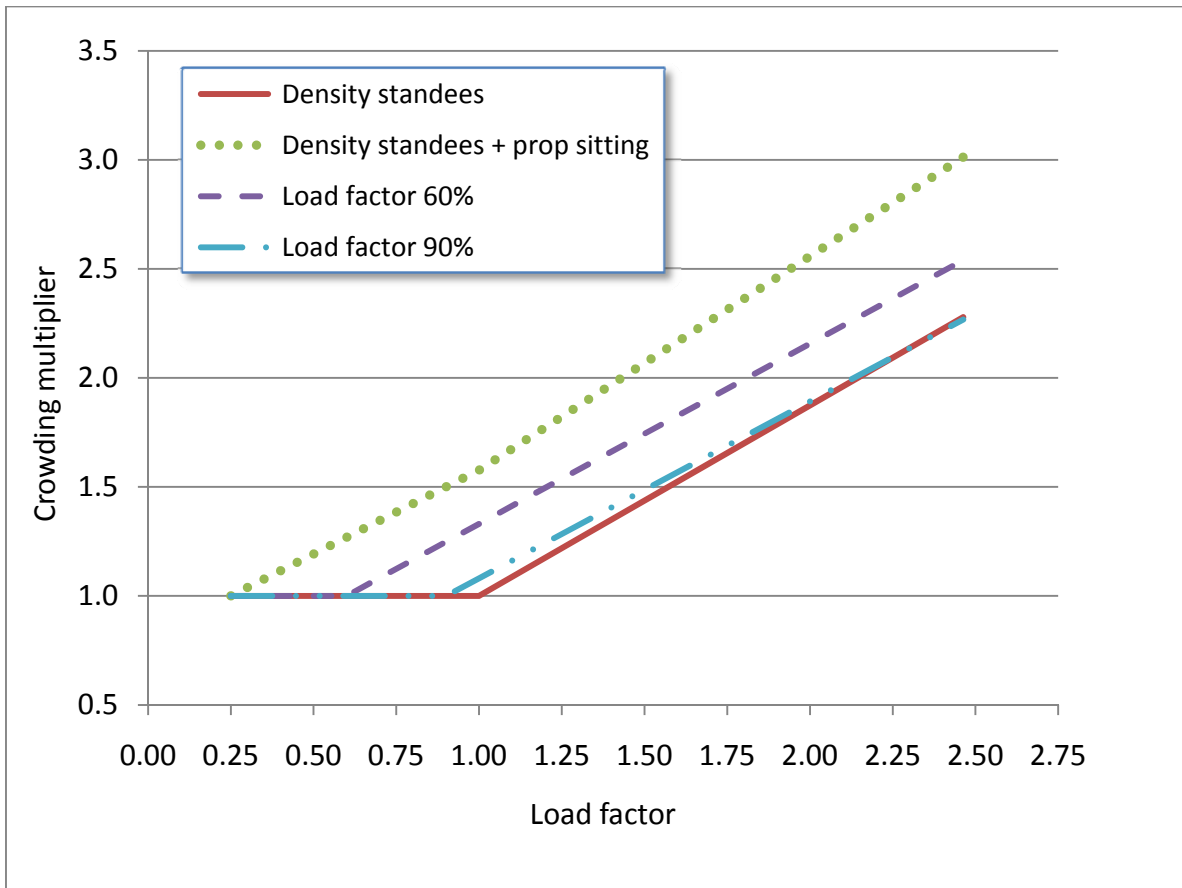**Figure 6: Value of in-vehicle time savings, EC models**

Figure 7: Crowding multiplier, EC models

4. Effect of crowding disutility on demand estimation

The choice models estimated in Section 3 are useful to analyse the effect on patronage prediction of explicitly including or ignoring crowding attributes in modal utility functions (eqns. 1 to 5). To this end, we model the choice between two modes – train and car – assuming different occupancy levels of the train alternative for a range of trip times, and use the parameters from the MNL models (Table 1). Assumed attribute levels are given in Table 2 and explained next. The attribute levels are such that resulting modal shares are in the range of the Sydney modal split, in which between 85 and 90 percent of motorised trips are made by car.

Table 2: Attribute levels for demand estimation

|	Access (=Egress) time [min]	Headway [min]	In-vehicle time [min]	Cost [$]
Train	5	10	t	$2.3 \; if \; t \leq 16.6$ $2.9 \; if \; 16.6 < t \leq 33.3$ $3.3 \; if \; 33.3 < t \leq 58.3$ $4.4 \; if \; 58.3 \leq t$
Car	2	-	$1.21t$	$15 + 0.074 \cdot 1.21t$

Travel time by car is assumed to be 21 percent greater than that of a train, given that on average, trains are 21 percent faster than the car-driver mode in Sydney (TDC, 2011). Train

fare is distance-based, with time thresholds in Table 2 calculated assuming an average train speed of 36 km/h (TDC, 2011). The car cost is assumed as a fixed $10 for parking plus $0.15 per kilometre and average car speed of 29.3 km/h (TDC, 2011).

Figure 8 shows the estimation of the train modal share for trips of 15 and 40 min (i.e., travel time by car is 18.2 and 48.4 min, respectively). The model that is insensitive to crowding levels (M1) underestimates demand if trains are uncrowded (load factor lower than 1.25-1.50, around 1 standee per square metre, depending on the model) and overestimates demand if trains are crowded (occupancy rates with more than 25 or 50 percent of passengers standing). On the other hand, models that are sensitive to crowding (M2 to M5) show how demand significantly drops as the occupancy level increases.
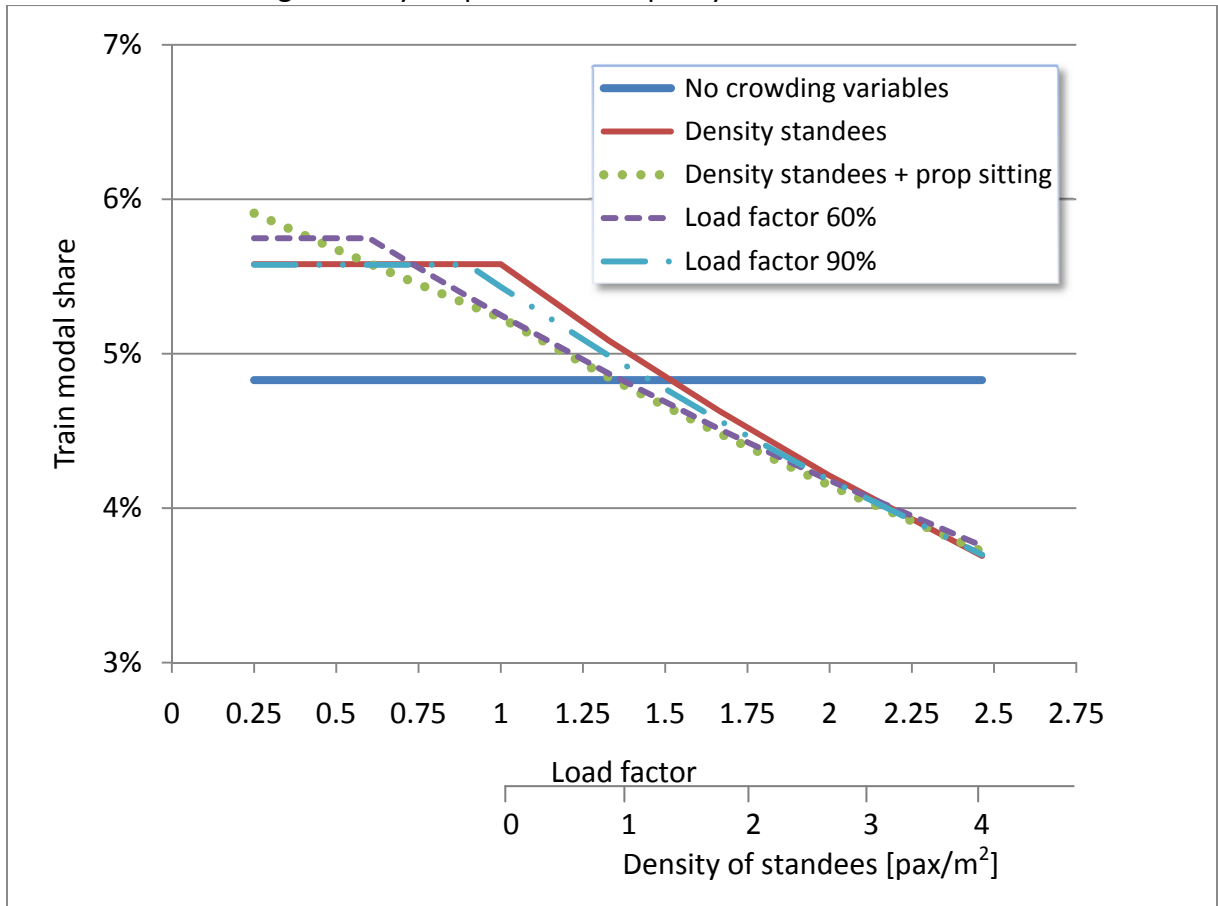
(a) Train travel time=15 minutes
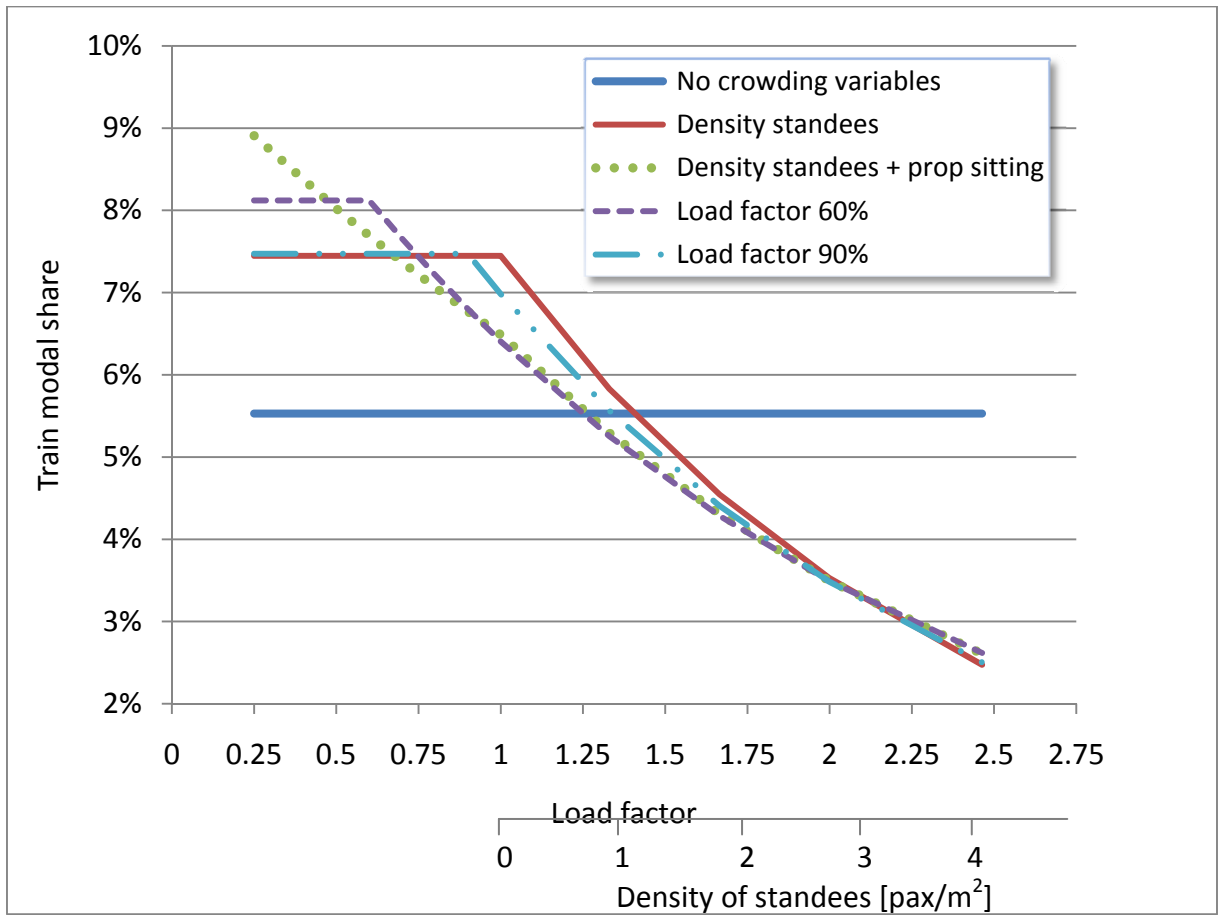
(b) Train travel time=40 minutes
Figure 8: Demand estimation for different crowding levels

The finding regarding demand estimation ignoring the effect of crowding on users' utility potentially has significant implications for demand estimation of proposed public transport enhancements, such as in the cost-benefit analysis of new light rail, heavy rail or bus rapid transit systems. Figure 8 suggests that if demand for the proposed service is estimated without explicit consideration of crowding as a source of disutility for passengers, demand will be overestimated if the system is designed to have an occupancy rate beyond a threshold θ^* (in our example, around 1 standee per square metre). Does such a threshold exist in other contexts, or assuming other attribute levels? Assuming a multinomial logit model, the threshold θ^* can be found analytically. Let V_{a1} and V_{t1} be the utilities of car and train in a model without crowding variables (model m1), and V_{a2} and V_{t2} the utilities of car and train in a model with crowding variables for the public transport mode (model m2). The probability of choosing train in m1 minus the probability of choosing train in m2 can be written as:

$$P_{t1} - P_{t2} = \frac{1}{1 + e^{V_{a1} - V_{t1}}} - \frac{1}{1 + e^{V_{a2} - V_{t2}}}$$

(6)

Utility V_{t2} can be expressed as $V_{t2} = V_{t2}^0 + \beta \theta t$, where V_{t2}^0 are the components of the utility that do not depend on the level of crowding, β is the marginal disutility of crowding

(negative), θ is a measure of the level of occupancy and t is in-vehicle time. Then, we can find a crowding level threshold above which the probability of using train in m1 is higher than in m2, as in expression (7)

$$P_{t1} > P_{t2} \Leftrightarrow \theta > \theta^* = \frac{\left(V_{a1} - V_{a2}\right) - \left(V_{t1} - V_{t2}^0\right)}{-\beta t}$$

(7)

where $-\beta$ is positive. Note that actual occupancy level θ is constrained, $\theta \in [0, \theta_{max}]$, and whether or not θ^* belongs to the interval $[0, \theta_{max}]$ depends on the estimation of parameters of models m1 and m2. Interestingly, threshold θ^* decreases with travel time as shown in Figure 7 for models M4 and M5, explained by the fact that for longer travel times the weight of crowding on the total travel utility increases; in other words, lower occupancy levels on long trips may have the same effect as higher occupancy levels on shorter trips.
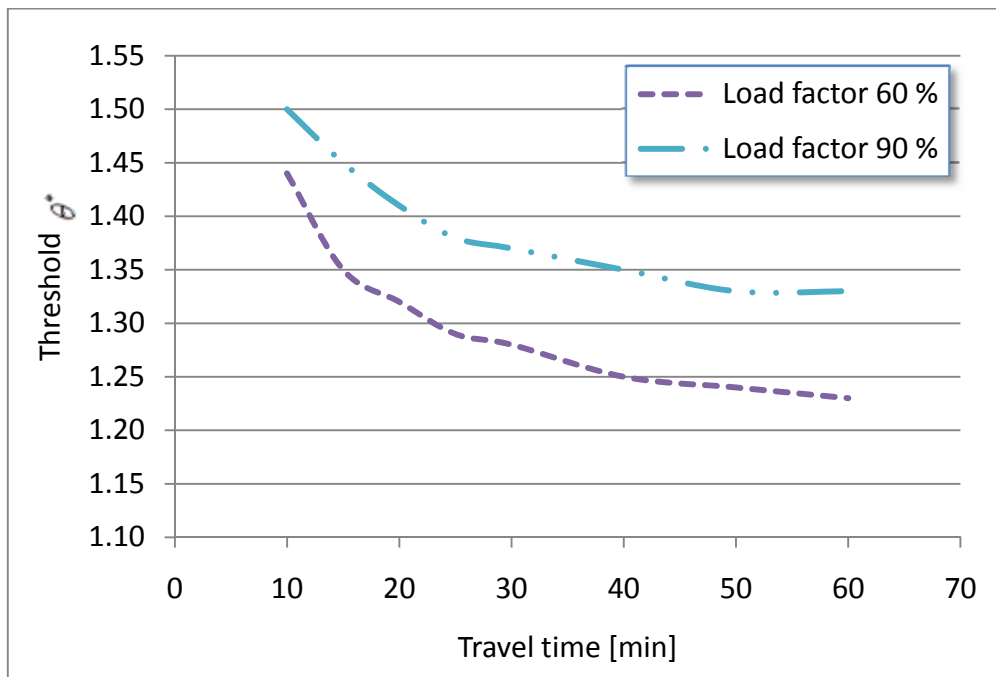

Figure 7: Train modal share for different crowding levels and travel times

5. Summary and Conclusions

This paper has provided a comprehensive review of the multiple effects that the crowding of passengers in public transport systems has on the quality and comfort of travelling, waiting and riding times, travel time variability, passenger wellbeing, vehicle and route choice, and the optimal value of a service frequency, size of vehicles and fares. A summary follows: (i) the impact of crowding on travel time through friction effects between passengers when boarding and alighting has been usually estimated using regression models that include the number of standees inside vehicles or at stations as an explanatory variable of dwell times. (ii) High average occupancy levels also increase the probability of vehicles circulating full,

and therefore, not being able to pick up passengers waiting at stops and stations, which increases waiting time and travel time variability. (iii) Amongst the impacts of the crowding phenomenon on passengers' health and wellbeing, authors have documented increased anxiety, stress and feeling of exhaustion, perceptions of risk to personal safety and security, feelings of invasion of privacy, propensity to arrive late at work and a possible loss in productivity for passengers that work while sitting on a train. (iv) These and other factors are likely to be behind the negative valuations that users have of experiencing high occupancy levels at stations, transfers and vehicles, which is obtained in demand models that account for a crowding effect on passengers' choices, most commonly through an effect on the valuation of travel time savings. (v) Different crowding levels between competing routes and unbalanced vehicle loads are also found to affect passengers' choices of route and vehicle. (vi) Finally, because the crowding externality increases the marginal cost of travelling, it should be accounted for in the design process of public transport systems, in particular in the determination of frequencies, vehicle size and fare, as shown in the public transport economic literature.

The second part of the paper is concerned with the effects on the valuation of travel time savings and estimation of demand of alternative assumptions regarding how sensitive users are to a crowding externality, in particular, of the minimum occupancy level that triggers a crowding effect on travel utility. Using data from Sydney, we have estimated crowding cost functions that depend on the availability of seats, the density of standees per square metre or the occupancy rate of vehicles. Two main findings are obtained that reveal the potential problems of omitting people's perception of crowding when estimating demand for public transport: (i) a model that assumes users as indifferent to the occupancy levels of vehicles overestimates the value of travel time savings (VTTS) for low load factors and underestimates VTTS for high load factors, and likewise (ii) a model that is insensitive to crowding levels underestimates demand if vehicles are uncrowded and overestimates demand if vehicles are crowded. The generalisability of these findings is not proven; however, assuming a multinomial logit model for mode choice, a load factor threshold that marks the underestimation or overestimation of demand when ignoring crowding is analytically found. More research is needed to explore if these findings hold with more complex choice models and in other contexts.

Regarding alternative crowding disutility specifications, we found that alternative assumptions concerning the threshold load factor that triggers a crowding effect do have an influence on the resulting VTTS. The effect is especially noticeably for low occupancy levels (all passengers sitting); however, for high occupancy levels, alternative crowding models tend to estimate similar VTTS. In other words, if a system is operated in highly crowded conditions, it makes little difference how sensitive were people to crowding while everyone is sitting.

The implications of the findings of this paper for cost benefit analysis and public transport policy are clear. The impact of crowding on demand and supply should be considered from the early stages of the appraisal of public transport projects, as the design of the system and the estimation of demand and social benefits rely on whether or not the multiple dimensions of the crowding phenomenon are accounted for in the formal assessment of projects. For example, where projects are marginal on benefit-cost ratios in the absence of allowing for crowding impacts, the inclusion of crowding can tip the balance (or at least

significantly improve the benefits) in supporting public transport investments that struggle to compete in benefit-cost terms with road investments.

Several directions of further research to obtain more comprehensive understanding on the implications of passenger crowding in public transport services are promoted. For instance, the negative impacts of crowding on the reliability of public transport services should be carefully analysed, together with the study of engineering and design factors in vehicles and stations that may help to reduce the effects of crowding on increasing travel time, and worsening the experience of travelling in public transport. Regarding sociodemographic factors, there is recent evidence on socioeconomic differences on the perception of crowding, and particularly on a bus being "full". A survey by Theler and Axhausen (2013) in Zurich, Switzerland, found perceptual differences of the level of occupancy that a bus should have to be considered "full" or "overcrowded" (for example, by age), which therefore implies a potential conflating of perception and taste in stated choice experiments (Theler and Axhausen, 2013), that should be taken into account in the analysis of future stated choice surveys. Finally, an integration of the studies on psychology and choice modelling is a promising venue of further research, in order to comprehend how the psychological aspects that influence the perception of crowding are linked to the perception of time, and to the willingness to pay to reduce the time spent in crowded environments in general, and in crowded public transport stations and vehicles in particular.

Li and Hensher (2013) provide a review of this broader literature.

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